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2D lattices of ferromagnetic nanoparticles as supermagnetics

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The interest in the systems of nanosize magnetic particles is accounted for by their potentiality as ultrahigh density magnetic recording media. It is assumed that each particle carries one bit of information and the maximal density of data recording can be increased to 10^{10} bit/cm^2. There are two basic limitations set on the geometrical sizes of such systems. First, the size of the particles should not be too small, as the lifetime of a particle with the assigned magnetic moment is $\sim \exp(KV/T)$, where K is the constant of the magnetic anisotropy, V the particle volume, T the temperature. The effect of the thermally induced rotation of the particle magnetic moment is called superparamagnetism. Second, the field of particles interaction in recording media must be much smaller than the energy of magnetic anisotropy. Otherwise, the particles demonstrate a collective behavior. One fundamental type of interaction between single-domain particles is the dipole interaction. The energy of two-particle interaction has the form

$$E = \frac{1}{2}\sum D_{ik}(\vec{x}-\vec{y})M_i(\vec{x})M_k(\vec{y}), \quad D_{ik}(\vec{x}) = \frac{\delta_{ik}}{x^3} - \frac{3x_i x_k}{x^5} \tag{1}$$

where $M_i(\vec{x})$ is the i-th component of the magnetic moment of a particle at point $\vec{x}$. It follows from (1) that to decrease the interaction energy one has to increase the interparticle distance. If there is a strong interaction in the system of superparamagnetic particles the unusual situation is possible. Indeed, the particle interaction energy can be neglected at rather high temperatures, and the system goes to a superparamagnetic state. With a decrease of the temperature the system became ordered due to the dipole interaction of particles. Such a state of the system was defined as supermagnetic [1]. The critical temperature of transition into this state depends on the characteristic value of the dipole interaction between particles

$$T_c \simeq M_\circ^2 V^2/R^3 \tag{2}$$

and for typical values of magnetization $M_\circ \simeq 1000$ G, $V \simeq 10^{-18}$ cm^3 and interpartical distance $R \simeq 10^{-5}$ cm, T_c is about to 100 K.

Due to anisotropic character of the dipole interaction (1) the type of the long-range order essentially depends on the parameters of a lattice. For example, two-dimensional lattices with a rhombic unit cell can have a ground state with both the ferromagnetic- and the antiferromagnetic type of ordering depending on a rhombicity angle [2]. It means that by varying a 2D lattice symmetry, a particle size and interparticle distance one can, in principle, create magnetics with assigned properties.

In this work we report some results of our investigations into such systems. We focussed on a investigation of 2D lattices with a rectangular unit cell. The easy magnetization axis in these systems is directed along the short side of the unit cell. The antiferromagnetic type of dipole ordering in the neighboring chains of the particles corresponds to the ground state at $T = 0$. Let us consider a simple case of noninteracting chains. At finite temperature

and zero external field there is no long-range order in this system. Despite the fact that the small perturbations spectrum does not have an acoustic branch, the long-range order is destroyed by nonlinear excitations (solitons). Fig. 1 presents the results of numerical simulation of the magnetization distribution in a dipole chain at a finite temperature. Note

Fig. 1. The thermoiduced soliton pair in dipole chain (computer simulation).

that the picture is similar to the one when the field is applied in the plane perpendicular to the chain.

The long-range order in 2D-system appears due to interaction of the chains. The chain interaction leads to interesting features of the hysteresis loop when the field is directed along the chains. In Fig. 2 we provide the results of numerical simulation for a system consisting of 80 chains, each having 6 dipoles (the ratio of the unit cell sides is 1:2). We can see that

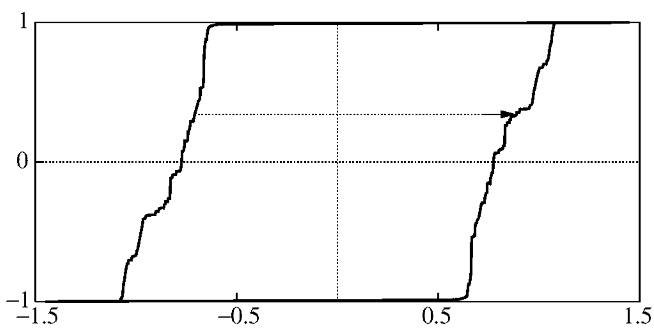

Fig. 2. The numerical simulation of the hysteresis loop in field directed along the chains.

the hysteresis loop is essentially a number of steps that correspond to the magnetization reversal of one chain. A similar dependence was studied in [3] for other systems and was called a "devil staircase". With a change of the derivative sign of the external field the system goes from one branch of the hysteresis loop to the other (shown by the dotted line in Fig. 2). These are, briefly, our ideas about the behavior of 2D lattices with a rectangular unit cell.

Two-dimensional lattices of nanosize magnetic particles were formed by the electron lithography method from permalloy films (Ni_3Fe) that were laser deposited on a substrate. Patterns were produced using C_{60} fullerene films as negative electron resists and Ti films as transmitting layer. In this way it is possible to form 2D lattices consisting of cylinder-shaped particles with a 15 to 100 nm diameter and a height equal to the thickness of the original (Ni_3Fe) film. According to the available data, the particles of this size should be considered single-domain ones. In the study of the magnetic properties we used a difference scheme comprising two semiconductor (InSb) Hall sensors with common potential contacts and independent current contacts. The size of the Hall cross of the sensors was $50 \times 100\,\mu$m, the thickness was $10\,\mu$m. The system under study was produced in the working zone of one sensor. The developed method allows to measure the magnetic field component perpendicular to the sensor plane in a wide temperature range. Figures 3 and 4 show the magnetization curves of a sample for different orientations of the external magnetic field

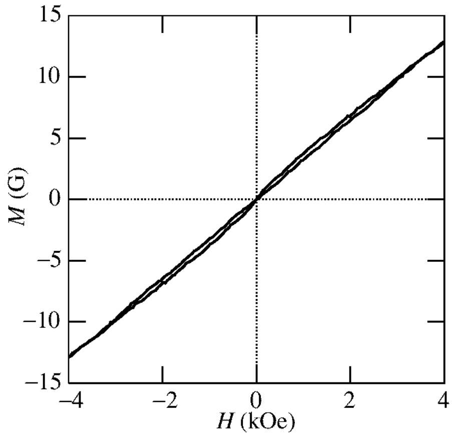

Fig. 3. The dependence of M_z on the magnetic field with $\theta = 45°$, $\phi = 0°$.

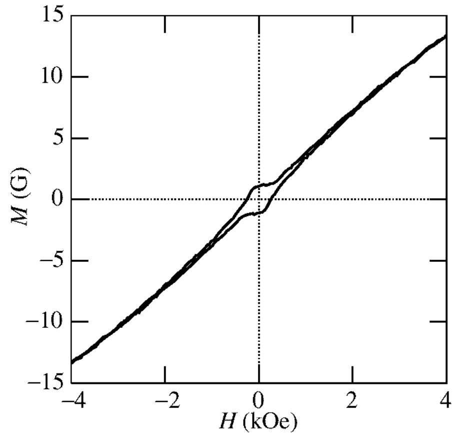

Fig. 4. The dependence of M_z on the magnetic field with $\theta = 45°$, $\phi = 90°$.

and $T = 4.2$ K. The particles form a lattice with a rectangular unit cell, 90×180 nm. The particles radius is 20 nm and the height is 45 nm.

The external field direction is characterized by two angles, θ and ϕ, where θ is the angle measured from the normal to sample and ϕ is the azimuthal angle measured from the axis directed parallel to the particle chains. The dependence of the magnetization curves on field orientation relative to the lattice axes cannot be interpreted in terms of individual particle properties and is a manifestation of the collective behavior of the particles. Note that the hysteresis loop in Fig. 4 has a remanent magnetization. This is likely to be connected with formation of nonuniform states (solitons) in the system of interest, which is close to a 1D system. When a field is applied perpendicular to the chains, there are two equilibrium states in the dipole chain, that have the same energy and differ in the sign of the longitudinal component of the magnetization. Hence, a temperature-induced domain formation is possible in these orientations. Measurements of the magnetization curves of a particle lattice with a square unit cell provide indirect evidence of the proposed hypothesis, as they have shown absence of remanent magnetization for any orientation of the external field. Numerical simulation also confirms the absence of solitons in a square lattice of dipoles.

In Figure 5 the magnetization curve for $\theta = 90°$, $\phi = 0°$ is presented. It is peculiar in that the magnetic susceptibility depends on the sign of change of the magnetic field.

The lower branch of the hysteresis loop corresponds to the increasing of the magnetic field, the upper one corresponds to the magnetic field decrease. If one changes the derivative sign of the magnetic field, the system goes from the one branch to the other. As was mentioned above, such a behavior is determined by multistability of the system. The question of whether or not this system undergoes a transition into a superparamagnetic state can be solved by investigating the temperature dependence of the observed effects. That such a dependence exists is proved by the qualitative changes occurring in the magnetization curve of a rectangular unit cell sample with an increase in the sample temperature to 77 K.

We believe that from the fundamental standpoint the obtained results are of great interest as an example of the behavior of a two-dimensional system with the exactly known inter-

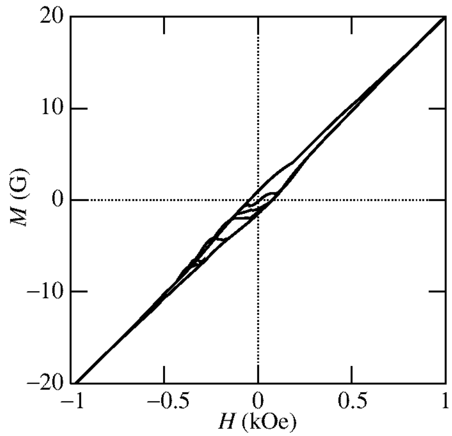

Fig. 5. The dependence of M_z on the magnetic field with $\theta = 90°$, $\phi = 0°$.

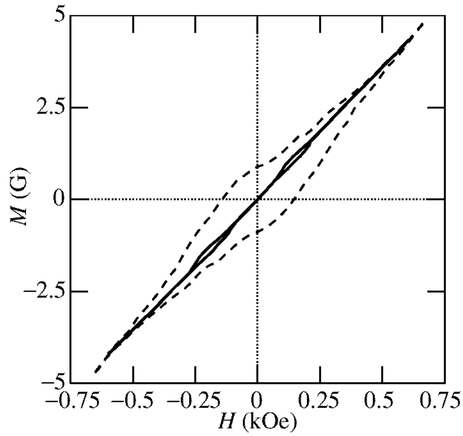

Fig. 6. The hysteresis loop change with a temperature (dashed line 4.2 K, solid line 77 K.

action. The samples, their fabrication technology and measurements could prove useful for ultrahigh density magnetic recording media under active development currently.

Acknowledgments

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References

[1] S. Morup, *Europhys. Lett.* **28**, 671 (1994).
[2] V. M. Rosenbaum, V. M. Ogenko and A. A. Chuiko, *Usp. Fiz. Nauk* **161**, 79 (1991).
[3] P. Bak and R. Bruinsma, *Phys. Rev. Lett.* **49**, 249 (1982)